

Planets in the Early Universe

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ABSTRACT

Several planets have recently been discovered around stars that are old and metal-poor, implying that these planets are also old, formed in the early universe together with their hosts. The canonical theory suggests that the conditions for their formation could not have existed at such early epochs. In this paper we argue that the required conditions such as sufficiently high dust-to-gas ratio, could in fact have existed in the early universe immediately following the first episode of metal production in Pop. III stars, both in metal-enhanced and metal-deficient environments. Metal-rich regions may have existed in multiple isolated pockets of enriched and weakly-mixed gas close to the massive Pop. III stars. Observations of quasars at redshifts $z \sim 5$, and gamma-ray bursts at $z \sim 6$, show a very wide spread of metals in absorption from $[X/H] \simeq -3$ to $\simeq -0.5$. This suggests that physical conditions in the metal-abundant clumps could have been similar to where protoplanets form today. However, planets could have formed even in low-metallicity environments, where formation of stars is expected to proceed due to lower opacity at higher densities. In such cases, the circumstellar accretion disks are expected to rotate faster than their high-metallicity analogues. This in turn can result in the enhancement of dust particles at the disk periphery, where they can coagulate and start forming planetesimals. In conditions with the low initial specific angular momentum of the cloud, radiation from the central protostar can act as a trigger to drive small-scale instabilities with typical masses in the earth to jupiter mass range. Discoveries of planets with low-metallicity hosts (e.g. HIP 11952 with $[Fe/H] \sim -1.95$) shows that planets did indeed form in the early universe, which may require modification of our understanding of the physical processes that produce them. This work is an attempt to provide one such heuristic scenario for the physical basis for their existence.

Subject headings: planetary systems: formation - quasars: abundances - cosmology: early universe

1. Introduction

A two-year gravitational lensing survey by the Microlensing Observations in Astrophysics (MOA) and Optical Gravitational Lensing Experiment (OGLE) groups towards the Galactic bulge (Sumi et al. 2011) has found ten events which can be attributed to Jupiter-mass planets. These microlensing planets are free-floating, in the sense that no host stars have been detected within about 10 AU. Recent estimates show that there can be up to 100,000 as many such planets as stars in the Galaxy (Sumi et al. 2011; Strigari et al. 2012). Three out of the 10 microlensing events from planets have galactic latitudes of $b \simeq -3^\circ$, and one has $b \simeq -6^\circ$, corresponding to the heights from 0.4 to 0.8 kpc. Therefore these planets are likely to belong to the thick disk population, where a considerable fraction (up to 30%) of stars is occupied by the oldest (Pop. II) Milky Way stars with mean metallicity $\langle [\text{Fe}/\text{H}] \rangle = -0.6$ (Zoccali et al. 2008; Bensby et al. 2011; Hill et al. 2011)¹. Thus these planets could also be old, formed in the early Milky Way Galaxy more than 10 Gyrs ago; their free-floating status a result of being ejected from the parent systems by planet-planet scattering events during the early stages of planetary systems life (e. g., Ford, Rasio & Yu 2006).

In general, a well-known planet distribution function peaking at solar metallicity (Udry & Santos 2007) is readily understood in terms of the thermodynamics of the gas from which the planets are formed: the smaller the gas metallicity, the weaker is the radiation cooling and therefore the higher are the gas temperature and the Jean’s mass. In the extreme case of primordial gas where the metallicity $[\text{Fe}/\text{H}] = -\infty$, the only source of cooling is from molecular hydrogen lines, and only extremely massive stars may be formed, $M > 80 M_\odot$ (eg. Schneider et al. 2003, Bromm & Larson 2004), which would have evolved rapidly and be extinct by now. However, it was suggested (Nakamura & Umemura 2001) that the fragmentation of filamentary primordial gas clouds could result in the formation of low-mass stars even in the absence of metals, with only molecular hydrogen as the main cooling agent. Recent simulations (Clark et al. 2011, Greif et al. 2011) demonstrated that the fragmentation process is rather environment-sensitive, such that gravitational instability may result in the formation of a group of low-mass ($M \sim 0.1 - 10 M_\odot$) protostars with a relatively flat

¹ $[\text{X}/\text{H}] = \log_{10} (\text{N}_\text{X}/\text{N}_\text{H})_\text{star} - \log_{10} (\text{N}_\text{X}/\text{N}_\text{H})_\odot$ and the subscript ‘ \odot ’ refers to the Sun.

initial mass function (IMF). The discovery of the extremely metal-poor ($Z \leq 7.4 \times 10^{-7}$)² low-mass ($M < 0.8 M_{\odot}$) star (Caffau et al. 2012) seems to confirm this conclusion. The formation of planetary fragments in gas with primordial chemical composition is, however, problematic, particularly because H_2 and HD molecules provide quick thermalization of gas with the cosmic microwave background, which limits the fragment mass to $M \gtrsim 0.1 M_{\odot}$ (Shchekinov & Vasiliev 2006).

The observed “metallicity effect” may be a result of a strong selection effect in that metal-poor Pop. II stars in the solar vicinity are at least two orders of magnitude less populous than those of solar metallicity (Gilmore et al, 1989; Dehnen & Binney 1998). Classical detection methods (radial velocity measurements and transits) limit detection of planets to nearby stars and thus most stars with detected planets have metallicities close to solar (see, for example, Fig. 1). Moreover, the metallicity effect is essentially limited to giant planets, which are obviously easier to detect. The recent population synthesis study (Mordasini et al. 2012) have shown that high metallicity favours the formation of a larger number of high-mass planets. The current ratio of giant ($M \geq 0.3 M_J$) to small-mass ($M < 0.3 M_J$)³ planets is ~ 3.4 , which can indicate that more metal-rich hosts are overrepresented (see Fig. 2).

In the lower mass domain — Neptune masses — this effect weakens (e.g., Mordasini et al. 2012). Indeed, host stars of Neptune-mass planets with precisely measured radial velocities (Cumming et al. 2008) show apparently a flat metallicity distribution (Udry et al. 2006; Sousa et al. 2011): a Gaussian peak at $[Fe/H] = -0.5$ transforms to a wide plateau in the range $[Fe/H] = -0.9$ to -1.5 . No metallicity trend is predicted for even lower-mass planets (Mordasini et al. 2012); moreover, recent results from Kepler mission (Buchhave et al. 2012) demonstrated that formation of small terrestrial-size planets does not necessarily require a metal-enriched environment.

That planets can form from matter with lower than solar metallicity is evident from the fact that about 50% of the giant planet-host stars have sub-solar metallicities (Setiawan et al. 2012). A number of giant planets at fairly low $[Fe/H]$ is now known (in 2012 there are 27 confirmed planetary hosts with $[Fe/H] \leq -0.4$, 3 of them with $[Fe/H] \leq -1.0$, and a pulsar B1620-26 planet in an $[Fe/H] = -1.5$ globular cluster M4) and this number is constantly increasing; the most recent discovery of two giant planets around an $[Fe/H] = -1.9$ F-dwarf HIP11952 suggests the age of the system of ~ 12.8 Gyrs (Setiawan et al. 2012).

²Z is the mass fraction of metals

³ M_J is the Jupiter mass

It is worth mentioning that when the first population statistics on exoplanets was published in 2007 (with very few low-metal hosts known), the relative percentage of metal-poor stars ($[\text{Fe}/\text{H}] \lesssim -0.6$) with planets in solar neighbourhood ($\sim 4\%$) was four times higher than the relative percentage of Pop. II stars ($\sim 1\%$) (as can be inferred from the Fig. 9 in Udri & Santos, 2007). According to the latest data (November 2012), this percentage now is around 2% (8 out of 472 stars with measured metallicity within 600 pc of the Sun have $[\text{Fe}/\text{H}] \lesssim -0.6$, see Fig. 3). With more discoveries, the relative number of metal-poor hosts may asymptotically approach the relative number of Pop. II stars in the solar neighbourhood. Thus, the question of principal importance arises of how to collect sufficient amount of metals to form planets, is it possible at all, and what could be the scenarios?

In this note we argue that the conditions for selective assembling of metals in the dust form could have existed even in the very early universe immediately after the formation of first massive stars, i.e. at the epoch when the first stellar light illuminated the universe at redshifts $z \gtrsim 10$ (see, for ex., Scannapieco et al 2006). It is worth mentioning in this connection that very recently Wickramasinghe et al. (2012) presented arguments that primordial free-floating (rogue) planets of solid hydrogen may account the whole “missing baryons” in the Universe. When recalculated for the Milky Way the number of such primordial planets is as numerous as $\sim 10^{14}$. In this work we however address rather the question of whether planets can form around stars with low metallicity. Moreover, we do not consider possible scenarios of planet formation in such conditions, but focus primarily on even a simpler issue: what mechanisms can provide accumulation of sufficient amount of metals (mostly in solid phase) to make the subsequent formation of planets possible within scenarios similar to those acting in the local Universe.

In Section 2 we bring evidence that in the very beginning of stellar nucleosynthesis in the universe, one might find enriched regions with the metallicities close to solar, or even higher, where planets can form under conditions analogous to the ones in local universe, provided that dust-to-metal ratio is of ~ 0.3 (as is normally assumed, see Maiolino et al. (2004) and Fukugita (2011)). In Section 3 we describe a possibility of enhancement of dust abundance in metal-deficient gas either due to the centrifugal force in peripheral regions of circumstellar protoplanetary accretion disks, when the specific angular momentum is sufficiently high, or due to the action of the radiation pressure from the host protostar in the conditions of small specific angular momentum. Section 4 summarizes our results.

We have used for this discussion the observational data from the Extrasolar Planets Encyclopaedia (<http://www.exoplanet.eu>) maintained by J. Schneider, from the Exoplanet Orbit Database (<http://www.exoplanets.org>) (Wright et al. 2011) and from NASA Exoplanet Archive (<http://exoplanetarchive.ipac.caltech.edu>). For the planet hosts with

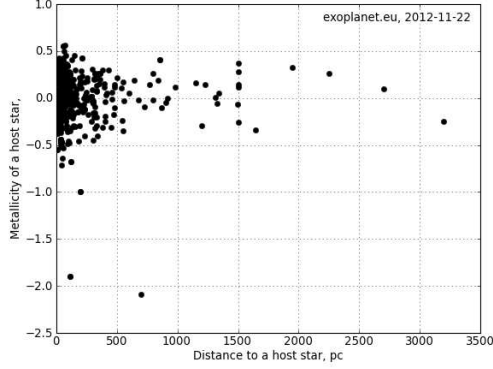


Fig. 1.— The plot shows the distribution of stars with confirmed exoplanets with metallicity (total 676). It can be seen that most of the planetary hosts are located in the solar vicinity, within $\lesssim 600$ pc of the Sun. This may indicate the selection effect in the suggested metallicity–planet-hosting dependence. This figure was made using the Extrasolar Planets Encyclopaedia at <http://www.exoplanet.eu>.

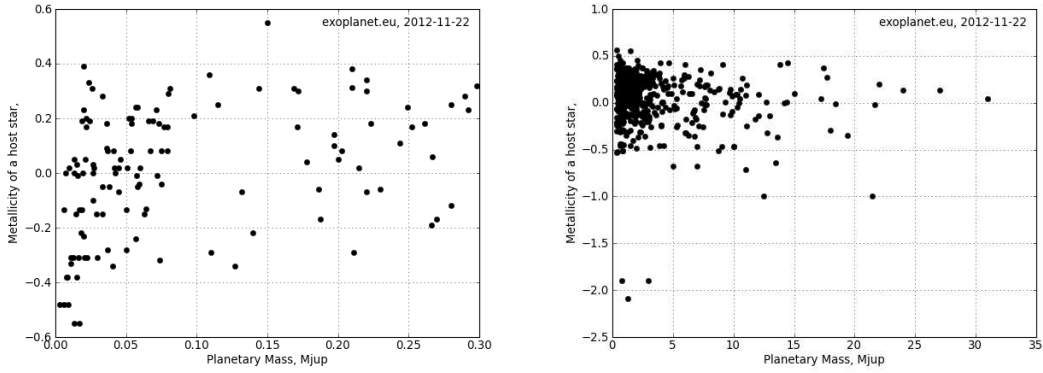


Fig. 2.— The plot shows the distribution of the exoplanets masses vs host metallicity. It is clearly seen that most of the detected planets are giants and the observed “metallicity effect” is neatly reproduced by giants, i.e., the planets with mass $M > 0.3 M_J$ (*Right*). In the small-mass domain, $M < 0.3 M_J$ (*Left*), the mass is nearly uncorrelated with metallicity. This figure was made using the Extrasolar Planets Encyclopaedia at <http://www.exoplanet.eu>.

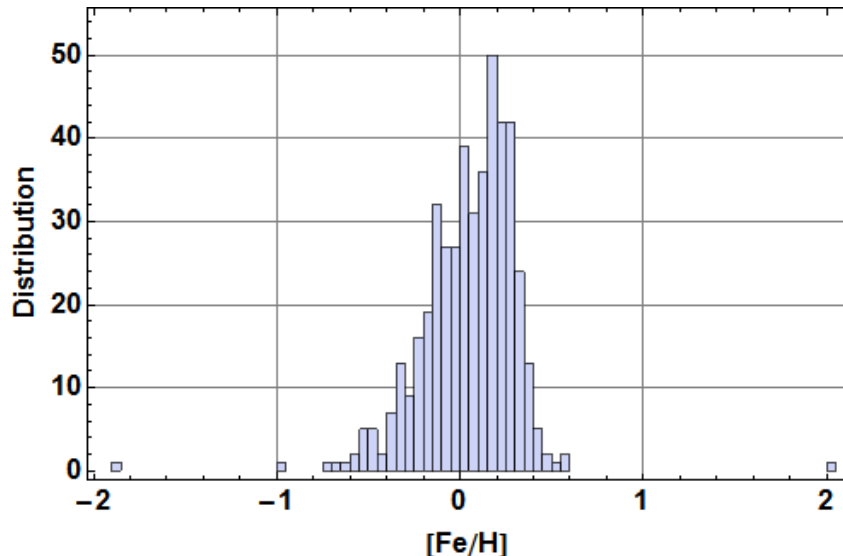


Fig. 3.— The plot shows the distribution of planets hosts in the solar vicinity (within 600 parsec of the Sun) as a function of host metallicity. Out of 472 planetary hosts with measured metallicity, 8 have $[\text{Fe}/\text{H}] \lesssim -0.6$ ($\sim 2\%$).

no metallicity data from the above-mentioned websites, we have used the values from Maldonado et al. (2012).

2. Metallicity in the early universe

It became clear from the very first detections of metals at high redshifts $z \simeq 6$ (Songaila 2001) that there are extreme variations of metallicity in the universe. Further observations confirmed this conclusion. Schaye et al. (2003) demonstrated that the abundance of carbon in the intergalactic medium can vary up to 2-3 orders of magnitude, particularly at lower redshifts ($z = 1.5 - 2.5$), while Simcoe et al. (2006) found many clumps and large clouds with metallicity varying between $[\text{X}/\text{H}] = -3$ and 0.6 toward quasar HS1700+6416 ($z_{\text{abs}} = 2.73$), here X denotes mostly the abundances of carbon, silicon, magnesium ions. Schaye et al. (2007) inferred a wide range (from $[\text{X}/\text{H}] = -1$ to 0.5) of metallicities in the absorption systems of several quasars at redshifts of $z_{\text{abs}} = 2$ to $z_{\text{abs}} = 3.2$. They concluded that the metallicity tends to be higher for smaller sizes of the absorbing gas clouds, as is predicted by the numerical simulations of metal-mixing by Dedikov & Shchekinov (2004).

From the theoretical point of view three basic models explaining the inhomogeneous

metal distribution in the universe have been described: patchy (unpercolated) distribution of metal-enriched bubbles around active (starburst) galaxies (Nath & Trentham 1997; Gnedin 1998; Ferrara et al. 2000); dependence of the metallicity of enriched bubbles on the host galaxy (Nath & Trentham 1997; Gnedin 1998; Ferrara et al. 2000; Shchekinov 2002), and inefficient (incomplete) mixing (Dedikov & Shchekinov 2004).

More evidence for highly inhomogeneous metal distribution at high redshifts comes from observations of Gamma-Ray Bursts (GRB) and particularly their optical afterglows: optical absorption spectra of the so-called GRB damped Ly- α systems – as opposed to QSO damped Ly- α systems – and the stellar light from GRB hosts show a high spread of metal abundance of about two orders of magnitude, with a weak redshift evolution and a relatively high mean $[X/H] = -0.7$ (Savaglio 2008; Savaglio et al. 2009), suggesting that the metal distribution is highly inhomogeneous in the host galaxies. Numerical simulations of mixing of metals in the ISM of the Milky Way Galaxy (de Avillez & Mac Low 2002) have shown that it can take as long as 120 Myr on length scales of 25 to 500 pc. If this time-scale is also applicable to GRB hosts, then homogenization of metals would take a considerable fraction of the Hubble time at $z = 8$. The high spread of metallicity in the GRB hosts then simply reflects the inhomogeneity of their ISM. Under such circumstances, a wide range of physical conditions favourable for the formation of planets around hosts with solar or near-solar metallicity can be found in the early universe.

3. Low-metallicity environment

Although we have shown that high-metallicity regions favourable for forming planets may be common in the early universe, the independence or even possible anti-correlation of the frequency of small planets with metallicity (Mordasini et al. 2012; Buchhave et al. 2012), together with the existence of old metal-poor stars hosting planets, such as for ex. HIP 13044 ($[Fe/H] \approx -2$, Setiawan et al. 2010) or HIP 11952 ($[Fe/H] = -1.8$, Setiawan et al. 2012) suggest that metallicity may not be the governing parameter for the formation of planets. It seems therefore worthwhile to consider possible mechanisms which can promote formation of planets in a metal-poor gas.

Core accretion scenario is recognized to account for most of detected planets. However, recent discoveries of planets which lie far from the possible parameter space for core accretion, for instance, planetary mass–metallicity relation, indicate that there may be several formation scenarios that lead to systems very different from the usual (see e.g., Mordasini et al. 2012). Such planets (for example, HR 8799, BD+20 2457 or HIP 1952) are difficult to account for by the core accretion. Planets found around stars with low metallicities or on very

wide orbits pose a challenge to the core-accretion scenario, and a gravitational instability model was proposed to better explain their formation (Dodson-Robertson et al. 2009). The scattering of these planets to wide orbits as a scenario of their formation (within the core accretion framework) was also rebutted in Dodson-Robertson et al. (2009). It seems natural to assume that stars with different metallicities form their planets by different mechanisms. Such an assumption is consistent with the findings that both giant and Neptune-mass planets discovered so far have rather flat metallicity distribution (Santos et al. 2004; Udry & Santos 2007; Sousa et al. 2008, 2011; Mayor et al. 2011). If the dominant planet formation mechanism were not changing with metallicity, we would rather see a monotonically increasing detection rate with $[\text{Fe}/\text{H}]$ for all metallicity range (Dodson-Robinson 2012).

Using order of magnitude estimate, we argue that, in the process of star formation from metal-underabundant material, immediately after the primeval enrichment in the early universe, selective assembling of dust around protostars can operate and enhance the local dust abundance to a sufficient level so that physical mechanisms (such as dust coagulation) leading to planet formation can start operating. At this stage, we believe that such an order of magnitude calculation is more practical than a sophisticated numerical approach involving the entire evolutionary path from dust coagulation through planetesimals to planet formation – a scenario which is still not fully understood even for our own Solar System.

3.1. Gravitational collapse versus gas metallicity

Two key ingredients controlling formation of planets are the presence of dust in a star-forming medium and the amount of rotation. It was recently recognized (see, for ex. Toddini & Ferrara 2001; Nozawa et al. 2003 and Maiolino et al. 2004) that dust particles are injected along with metals right from the very initial metal-pollution episodes. We therefore assume, following Fukugita (2011), the mass abundance of dust to be $\mathcal{D} \simeq 0.3Z$, where $Z = Z_{\odot} \mathfrak{z}$ is the absolute mass abundance of metals.

It is obvious that in early galaxies with metal-poor gas, the low amount of metals and dust restricts the formation of rocky planets. The maximum number of Earth-size planets that can form in a protostellar cloud of mass M is $\mathcal{N} \sim \mathcal{D}M/M_E$ where M_E is the Earth mass. Defining $m = M/M_{\odot}$, we obtain $\mathcal{N} \sim 3 \times 10^3 m \mathfrak{z}$ per cloud. For the protostellar cloud of mass $m = 10$ and even at $\mathfrak{z} \sim 10^{-2}$ and efficiency of planet formation of 1%, we obtain $\mathcal{N} \sim 3$. If we assume the star formation efficiency at 10% (i.e. each cloud of $m = 10$ produces one star), it would mean that every star may have 3 planets. Note that when applied to the cloud with solar metallicity, this estimate gives up to 300 planets per star. Although it was recently recognized that multiplanetary systems are rather a rule than an exception, the

most populous exoplanet systems yet detected, HD 10180, has 7 confirmed planets (Lovis et al. 2011). It is likely that the population of planets in a given system is usually less than 10 (more likely 3) because of the instability of planetary orbits on time scales greater than 1 Myr (Juric 2006; Vedas et al. 2011). The detection of multi-planetary systems can, however, be impeded by the high inclination of the planetary orbits to the line of sight (Tremaine & Dong, 2012) and/or by the weak and tangled wobbling of the host star produced by distant planets.

It is assumed after Hoyle (1953), that during gravitational contraction a cloud radius R can be subjected to a successive (hierarchical) fragmentation, if radiative cooling is sufficiently efficient to keep temperature growing slower than $T \propto n^{1/3}$, such that the Jean’s mass $M_J \simeq 30T^{3/2}n^{-1/2} M_\odot$ decreases with gas density n . More recent numerical simulations showed that successive fragmentation continues while gravitational contraction is isothermal, i.e. $\gamma = d \ln p / d \ln \rho \leq 1$ (Li et al. 2003). In general, since optical depth grows as $\tau \propto R^{-2}$, a contracting cloud becomes eventually opaque, even though at initial stages it is always optically thin. This moment finalizes the isothermal regime and determines the minimum stellar mass.

A more recent development of this approach applied to the problem of Pop. II.5 stars (stars formed right after Pop. III) was developed by Omukai et al. (2005), Schneider et al. (2006) and Schneider et al. (2012). They considered a parcel of gas density $\rho(t)$ belonging to a contracting fragment whose temperature is determined by heating from gravitational compression, and cooling is determined by radiation liberated in inelastic collisions,

$$\frac{1}{\gamma - 1} \frac{k}{\mu m_H} \frac{dT}{dt} = -p \frac{d}{dt} \frac{1}{\rho} - L, \quad (1)$$

where m_H is the hydrogen mass, μ is the mean molecular weight and L is the cooling rate. Eq. (1) determines the evolutionary track $T(\rho)$. For a given model of dust particles and their mass fraction, and when all possible cooling mechanisms, such as cooling in atomic (CI, CII, and OI) and molecular (H_2 , HD, OH, CO) emission lines, cooling in continuum due to thermal emission by dust particles and others are included, the minimum mass of protostellar fragments is $\sim 0.3 M_\odot$ for metallicity $[X/H] = -7$, and $\sim 1 M_\odot$ for $[X/H] = 0$ (Omukai et al. 2005). Therefore, within these assumptions, the masses of protostellar condensations are rather insensitive to gas metallicity from which they form, but can be sensitive to a dust model and to the depletion factor of refractory elements on dust surface (Schneider et al. 2012). For simplicity, we restrict ourself with the models described by Omukai et al. (2005) and Schneider et al. (2006).

The cloud density at which fragmentation stops is, however, rather sensitive to metallicity and can be roughly approximated as $n \sim 10^5 \mathfrak{z}^{-1.5} - 10^2 \mathfrak{z}^{-2} \text{ cm}^{-3}$, depending on the mass

of a progenitor of the polluting supernova (SN), $195 M_\odot$ and $22 M_\odot$, respectively (Schneider et al. 2006). This can mean that less-enriched protostellar clouds and, as a consequence, the circumstellar (protoplanetary) disks when established, must rotate faster by factor of $n^{2/3}$ if they had equal specific angular momentum j_0 on average. The specific angular momentum of star-forming molecular clouds in the Milky Way is $j_0 \sim 30 \text{ pc km/sec}$, nearly an order of magnitude lower than the specific angular momentum in the interstellar medium (Blitz & Williams 1999), which we will assume here as a reference value $j_0 = 10^{25} \Lambda \text{ cm}^2/\text{sec}$, with Λ as a free parameter.

3.2. Centrifugal assembling of accreting dust

Planets seem to form during subsequent evolution of such a protostellar cloud, after formation of embryo disk through coagulation, settling of dust onto plane and followed fragmentation. The Toomre parameter for the stability of disk (Binney & Tremaine 1987),

$$Q = \frac{\Omega c_s}{\pi G \Sigma}, \quad (2)$$

seems to be relatively insensitive to metallicity as both angular velocity Ω and surface density Σ scale with the radius as R^{-2} . Q is sensitive to the free parameter Λ , which can vary in a wide range. The sound speed c_s at the time when fragmentation stops and accretion disk is to be formed depends on metallicity, $c_s \propto \mathfrak{z}^{-1/4}$, and can vary from 0.3 to 3 km/sec for $\mathfrak{z} = 0.1 - 10^{-6}$ (as inferred from Omukai et al. (2005) and Schneider et al. (2006)). Later on, when the circumstellar accretion motion settles on to the disk, the sound speed relaxes to the value determined by the heating from central star (protostar) and by the viscosity in the disk. From this point of view, and particularly accounting for the fact that Λ varies in a wide range and might be low, one can conclude that the conditions for gravitational instability in circumstellar disks today and in the early galaxies are similar.

At the initial stages when the disk has only just formed, dust particles move tightly coupled to gas. This is a fast rotation with velocity $v_\phi = \Omega R$ and a slow inward accretion with velocity $v_r \sim \alpha v_d^2 / \Omega R$, $\alpha \leq 1$, where v_d is the dispersion velocity in gas (see Pringle 1981). Assuming the turbulence in the disk to be subsonic, let $v_d \leq c_s \propto \mathfrak{z}^{-1/4}$. Dust decouples from gas when the collisional drag rate,

$$\nu_d \sim \frac{\pi a^2 m_H v_d n}{m_d} \propto a^{-1}, \quad (3)$$

becomes smaller than the rotation rate Ω due to the growth of dust particles; m_d and a are the grain mass and radius, respectively. The total rate of the dust growth ν_g through coagulation

and freezing of heavy elements on dust surface can be estimated as

$$\nu_g(a) = \frac{1}{a} \frac{da}{dt} \sim \frac{sm_H v_d n Z}{a \bar{\rho}}, \quad (4)$$

where $\bar{\rho}_g \sim 3 \text{ g/cm}^3$ is the density of a dust grain and $s \lesssim 1$ is the mean sticking coefficient in dust-dust and atom-dust collisions; tight collisional coupling between dust and gas is explicitly assumed. After time $t = 2\pi N/\Omega$, corresponding to N rotational periods of the disk, the grain radius can grow up to

$$a \sim \frac{sm_H n v_d Z}{\bar{\rho}} \frac{2\pi N}{\Omega}, \quad (5)$$

where we explicitly assumed that all dust particles are of equal radius. With the growth of dust grains, the collisional drag rate ν_d decreases as

$$\nu_d \sim \frac{\Omega}{2\pi s Z N}, \quad (6)$$

so that after $N \gtrsim (sZ)^{-1}$, $\nu_d/\Omega \ll 1$, dust particles decouple from the gas motion. Though they continue the frozen rotation, the inward radial motion slow down dramatically, $v_{dr}/v_r \sim O(v_r^2/v_\phi^2)$, and dust piles up in a ring. This happens when the dust particles have moved inwards by

$$\Delta R \sim \frac{2\pi N v_r}{\Omega} \sim 2 \times 10^{17} \frac{m}{\Lambda^2 n s Z}, \quad (7)$$

where m is the mass of a protostellar cloud in solar units. The gas inflow continues, but its faster decoupling ($\Delta R/R$ is small) implies that it is left behind at larger radii. When the density at last fragmentation episode $n \propto \mathfrak{z}^{-b}$ ($b = 1.5 - 2$, Schneider et al. 2006) is substituted, it becomes readily seen that after decoupling, dust particles in metal-deficient disks accumulate mostly in outer regions of the disk as $\Delta R \propto \mathfrak{z}^{b-1}$, i.e. the lower the metallicity of the disk the farther in the disk dust accumulates, everything else (e.g. Λ , m) being equal. For the abundance pattern and dust yield corresponding to a $M = 22 M_\odot$ progenitor, we numerically obtain

$$\frac{\Delta R}{R} \sim \frac{0.1 m^{2/3} \mathfrak{z}^{1/3}}{\Lambda^2 s}, \quad (8)$$

which shows that in metal-deficient circumstellar disks dust accumulates in external regions, while in the cases with $\mathfrak{z} \sim 1$ dust occupies nearly the entire disk. Asymptotically, the enhancement factor in the region of accumulation is approximately $\eta \sim \Delta R/\delta R$; here δR is the thickness of the ring where dust accumulates, estimated as the distance travelled by dust particles in the radial direction before being decoupled, $\delta R \sim 3 \times 2\pi v_r/\Omega$, a factor of 3 is

assumed for concreteness. The enhancement factor is then readily estimated as $\eta \sim (3sZ)^{-1}$, resulting in the enhanced metallicity in the ring $\mathfrak{z}_e \sim \eta\mathfrak{z} \sim (3sZ_\odot)^{-1} \gtrsim 1$.

After decoupling, the gas is at a higher temperature and resists gravitational collapse, while the dust has smaller velocity dispersion and is thus able to form gravitationally-bound objects. The Toomre parameter of dust Q_d within the ring decreases inversely proportional to dust content in it and, because the dust velocity dispersion σ_d ($\sigma_d \ll R\Omega$) decreases as $\sigma_d \propto a^{-3}$,

$$Q_d = \frac{\Omega\sigma_d}{\pi G\Sigma_d} \sim 10\Lambda v_d \left(\frac{a_0}{a}\right)^3, \quad (9)$$

where a_0 is the initial radius of the grain and we have assumed that before decoupling dust and gas velocity dispersions are equal, $\sigma_d = v_d$. It can be readily shown that during the growth stage, the grain radius a increases considerably by factor $a/a_0 \sim 50\mathfrak{z}^{-1/3}m^{2/3}$. This means that Q_d gradually falls below unity. As a result, dust particles in the ring start assembling due to self-gravity, with characteristic free-fall time

$$t_{ff,d} = \sqrt{\frac{3}{32\pi G\rho_{d,e}}}, \quad (10)$$

where $\rho_{d,e}$ is the enhanced dust density in the ring. It can be expressed as $\rho_{d,e} = 0.3\rho Z_\odot \mathfrak{z}_e$, where $0.3 Z_\odot \mathfrak{z}_e$ is the mass fraction of dust in the ring and $\rho \sim m_H n$, and n is assumed to be close to the value at the final fragmentation (Omukai et al. 2005), i.e. $n \sim 10^2 \mathfrak{z}^{-2}$. The free-fall time is then

$$t_{ff,d} \sim \frac{10^{15}}{\sqrt{0.3Z_\odot \mathfrak{z}_e n}} \sim \frac{10^{16}}{\sqrt{n\mathfrak{z}_e}} \lesssim 10^{15} \mathfrak{z} \text{ sec}. \quad (11)$$

It is readily seen that the assembling can take tens to hundreds of rotation periods, depending on the mass of the protostellar cloud, rotation free parameter Λ and metallicity \mathfrak{z} .

It is clear that the overall picture depends on the dust optical model, i.e., on the enrichment scenario. When, for example, the abundance pattern of a pair-instability SN with a $195 M_\odot$ progenitor is applied, for which Omukai et al. (2005) and Schneider et al. (2006) predict the density at the final fragmentation step $n \sim 10^5 \mathfrak{z}^{-3/2}$, decoupling condition becomes insensitive to metallicity and dust occupies the whole disk. As a consequence, the dust distribution throughout the disk becomes very dilute, making its gravitational accumulation a very slow process. At such conditions, however, dust can be selectively assembled by the radiation from the central star through the “mock gravity” instability.

3.3. Radiation-driven assembling of dust clumps

When either dust optical properties critically deviate from the model used in above estimates, or angular momentum is low $\Lambda \ll 1$, the described scenario of centrifugal dust accumulation does not operate anymore. In such conditions, a complementary mechanism, which selectively drives dust particles to form clumps, connected with radiation pressure from a central stellar or protostellar object, can come into play. Let us discuss briefly this scenario assuming for the sake of simplicity $\Lambda \ll 1$. When a dusty gas is illuminated by an external radiation field, a mock gravity instability can develop with the growth rate similar to the one of Jean’s instability (Field 1971),

$$\Gamma^2 = f(\sigma)\Gamma_r^2 - k^2 c_{dg}^2. \quad (12)$$

Here $\Gamma_r = \kappa c(\rho_r/\rho)^{1/2}$, where κ is the inverse length of photon extinction and c is the light speed. Radiation density is $\rho_r = 4\pi F/c^3$, where F is the photon energy flux, $\rho = \rho_d + \rho_g$ is the total dust and gas mass density, and k is the wavenumber, $\sigma = k/\kappa$, the normalized wavenumber, $f(\sigma)$ is defined by

$$f(\sigma) = \frac{1}{3}\sigma^2 \left[\frac{1-\beta}{\beta} + \frac{1}{1-\tan^{-1}\sigma/\sigma} \right], \quad (13)$$

where β is the fraction of incident radiation absorbed by a dust grain. The sound speed in dust-gas mixture, c_{dg} , is essentially equal to the sound speed in gas, $c_{dg} \simeq c_g$. It can be readily seen that for all wavenumbers of interest, $\sigma \gg 1$, in which case the asymptotics of $f(\sigma) \sim Q_a$, where Q_a is the absorption efficiency (Field 1971). In the long-wavelength limit, the wavenumbers are less than the critical wavenumber, $k < k_c = \Gamma_r/c_{dg}$, and perturbations in such dust-gas mixture become unstable against aperiodic growth of clumps under the action of radiation pressure.

The optical flux from a nearly-solar mass protostar at distance r is

$$F \simeq \frac{pL_\odot}{4\pi r^2} \simeq 2 \times 10^5 r_{10}^{-2} \text{ erg cm}^{-2} \text{ sec}^{-1}, \quad (14)$$

where r_{10} is the distance from star in units of 10 AU and p describes the deviation of the luminosity from the main-sequence (MS) solar luminosity before settling of a protostar onto the MS. In Eq. (14) we explicitly assumed $p = 10$ following conclusions by Palla & Stahler (1993). We can estimate the inverse extinction length as

$$\kappa = \pi a^2 \mathcal{D} Z_\odot \frac{3\mu m_H n}{m_d}, \quad (15)$$

where dust, as above, is assumed monodispersal. For typical parameters, we obtain the critical length

$$\lambda_c = \frac{2\pi}{k_c} = \frac{2\pi}{\kappa} \frac{c_g}{c} \left(\frac{\rho}{Q_a \rho_r} \right)^{1/2} = \frac{8\pi \bar{\rho} a}{3\mathcal{D} Z_\odot \mathfrak{z} \rho} \left(\frac{\rho}{Q_a \rho_r} \right)^{1/2} \frac{c_g}{c}, \quad (16)$$

here density of dust particles is assumed as $\bar{\rho} = 3 \text{ g cm}^{-3}$.

The corresponding critical mass is

$$M_c \sim \rho \lambda_c^3 \simeq \left(\frac{8\pi \bar{\rho} a}{3\mathcal{D} Z_\odot \mathfrak{z}} \frac{c_g}{c} \right)^3 \frac{1}{(Q_a \rho_r)^{3/2}} \frac{1}{\rho^{1/2}} \sim 2 \times 10^{31} \frac{r_{10}^3 T_{100}^{3/2} a_{0.1}^3}{n^{1/2} p^{3/2} \mathfrak{z}^3} \text{ g}. \quad (17)$$

Here $T_{100} = T/100 \text{ K}$ is the temperature in the circumstellar cloud and $a_{0.1} = a/0.1 \text{ } \mu\text{m}$. If one assumes that the density in such a cloud, surrounding the central protostar, is close within a factor $\nu < 1$ to the density at the time of last fragmentation (when the protostar has formed), the critical mass becomes

$$M_c^{(1)} \sim 10^{26} \nu^{-1/2} \mathfrak{z}^{-9/4} r_{10}^3 \text{ g}, \quad (18)$$

for dust composition related to a $\sim 195 M_\odot$ polluting SN, and

$$M_c^{(2)} \sim 3 \times 10^{27} \nu^{-1/2} \mathfrak{z}^{-2} r_{10}^3 \text{ g}, \quad (19)$$

for a $22 M_\odot$ SN dust composition, as inferred from Schneider et al. (2006); here $T_{100} = 0.1$ and $p = 10$. In both cases, M_c is close to the Jovian mass for $r_{10} = 1$, when the metallicity range $\mathfrak{z} = 0.1 - 0.01$ is assumed. Note that the corresponding mass of metals, $M_z = Z M_c = Z_\odot \mathfrak{z} M_c$, is either equal or even less than the mass of the Earth. It is interesting to note that the critical mass depends on the distance from the central protostar $M_c \propto r^3$, which is obviously caused by the fact that the instability is driven by the protostar radiation — the farther from the protostar, the weaker is the instability, and the longer is the unstable wavelength: at $r = 1 \text{ AU}$ the critical mass is already in the range of Earth masses. It is worthwhile to stress here that low specific angular momentum $\Lambda \ll 1$, that we have assumed in this section, does not mean that dust clumps would fall onto the central star and evaporate. Firstly, $\Lambda \ll 1$ implies only that the disks form at much later stages than described by Eq. (8), that is, dust does not decouple centrifugally. Secondly, it can be readily seen that the characteristic growth time of the mock gravity instability, $\tau_r \sim 10 a_{0.1} r_{10} \text{ yr}$ (for a $22 M_\odot$ dust composition of Schneider et al., 2006), is comparable (or shorter at radii $r_{10} > 1$) to the free-fall time of clumps onto the star, $t_{ff} \sim 10 r_{10}^{3/2} \text{ yr}$ (Eq. 11). When, on the contrary, angular momentum is not necessarily $\Lambda \ll 1$, an additional positive energy – epicyclic motion \varkappa^2 (Pringle & King, 2007) – enters the r.h.s. of Eq. (12) along with the sound mode $k^2 c_{dg}^2$, which increases critical lengths and masses of the fragments formed.

4. Conclusions

1. Recently discovered planets around metal-deficient stars, such as HIP 13044 and HIP 11952, indicate that planets can form in the early universe. Free-floating planets observed in MOA experiment can also be old as they are located in the region of stellar Pop. II (in this sense, they belong to Population II planets — planets formed after the initial episodes of enrichment by Pop. III stars, either *in situ* with Pop. II hosts or *ex-situ* from direct gas collapse). At the same time, it cannot be excluded that a well-established increase of metallicity towards the Galactic center can contaminate this expectation.
2. On the other hand, observations definitely show that metals in the universe are mixed very inefficiently, resulting in a highly inhomogeneous distribution of metallicity in the universe: it is clearly seen both in stellar populations of GRB hosts and in the IGM clouds of GRB damped Ly- α systems. As a consequence, even in a high redshift universe (say, $z \gtrsim 6$), the conditions can exist for formation of planets with normal metallicities, either anchored to host stars or free-floating in the star-forming clouds.
3. Planets can also form in metal-poor environments:
 - In the cases when the specific angular momentum in protostellar molecular clouds is comparable to the value of the Milky Way molecular clouds. In such case, they form preferentially in outer regions of circumstellar disks due to formation of dust rings, where dust particles are decoupled from gas and have negligible inward radial velocity.
 - If, however, rotation of starforming clouds is small and circumstellar gas accretes quasi-spherically, the radiation from the central protostar can stimulate formation of clumps through the mock-gravity instability caused by radiation pressure on dust grains. The characteristic masses of such clumps for fiducial parameters are close to the Jovian mass. Such clumps can, in principle, give rise to the formation of (free-floating) planets in a metal-deficient environment of the early universe.

Therefore, the conditions favourable for planet formation — sufficiently high dust-to-gas ratio — could have existed in the early universe in both metal-rich and metal-poor environments, which can explain the existence of planets with an age of up to 13-14 Gyr in the local universe. These conditions, that we have envisaged here, are however only necessary though not sufficient, so that further observational and theoretical study are needed in order to firmly substantiate this conclusion.

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